Considerations about Winglet Design

Bento S. de Mattos  Antonini P. Macedo  Durval H. da Silva Filho

Empresa Brasileira de Aeronáutica S.A.
Av. Brigadeiro Faria Lima, 2170
12.227-901 São José dos campos – SP – Brazil

From the beginning of aviation designers are searching for methods and technologies for reducing the required fuel burn of commercial aircraft. Wingtip devices aim the reduction of induced drag, which is responsible for 30-40% of the total drag of a transport-aircraft at long-range cruise condition and for considerably downgrading the climb performance of an aircraft. Winglet alongside with tip tanks, raked wingtips, aligned fans belong to this class of devices. Better investigation in this field employing CFD tools and extensive wind-tunnel testing has allowed the rising of efficient winglet designs in recent times. Several of newly designed aircraft configurations embody winglets and many older ones are being retrofitted. However, there are discussions concerning the best cost/benefit of reducing induced drag of a transport plane with wingtip devices. Another big issue is the associated penalties to the configuration caused by winglets when compared to a simple wingtip extension. This paper addresses some of these issues based on the expertise obtained designing winglets for several aircraft configurations, ranging from a business jet and a twinjet airliner for 70 passengers to an AEW&C military airplane.

Introduction

In 1979 and 1980, NASA Dryden Flight Research Center was involved with general aviation research with the KC-135 aircraft. A winglet, developed by Richard Whitcomb of the Langley Research Center, was tested on the jet aircraft6. This winglet concept was tested on a KC-135A tanker loaned to NASA by the Air Force. The research showed that the winglets could increase an aircraft's range by as much as 7 percent at cruise speeds. The first application of NASA's winglet technology in industry was on General Aviation business jets, but winglets are now being incorporated into most commercial and military transport jets, including the Gulfstream III, IV and V (renamed to G550) business jets, the Boeing 747-400 and McDonnell Douglas MD-11 airliners, the McDonnell Douglas C-17 military transport, and Embraer aircraft. In recent years, many after market modification kits have been offered for adding winglets to aircraft, which did not originally have them.

By using CFD tools and wind-tunnel testing Embraer was able to design winglets for several of its aircraft. Some of these aircraft were designed and certified without winglets, whereas others were conceived envisaging the benefits of winglets from the beginning. One of the technical challenges then became how to add winglets to existing wings, achieving significant aerodynamic improvements with minimal structural weight penalty and minimal system changes.

The winglet development at Embraer began in 1989, when Embraer conducted subsonic wind-tunnel tests at the Centro Técnico Aeronáutico (CTA), a Brazilian Research Agency for Aeronautics and Astronautics. A parametric study was then performed and some winglet configurations were selected for further analysis. The tests results also indicated potential benefits of fitting winglets with a smooth transition onto the tips of existing aircraft wings. A prototype of the twin-pusher CBA-123 was flown equipped with a preliminary design in February 1991 to gather flight-test data.

Following this early effort, the winglets of the EMB 145 AEW&C (Airborne Early Warning & Control) were designed in the early 1990s based on wind tunnel research and flight tests performed by means of CFD techniques employing inverse design in the 1989-1991 period7. Improvements of the winglet airfoil were performed with both MSES8,9 and XFOIL10 codes. The tip of the winglet suffered some redesign in order to displace the vortices outward more efficiently. The final winglet configuration was very effective, allowing Embraer to significantly increase the range of
the aircraft, which was conceived to fly at a subsonic condition with a high lift coefficient.

In the sequence, a new winglet configuration was designed for the Legacy Business Jet, which cruises at Mach number of 0.80 and higher lift coefficient. Finally, the Embraer 170/175 and the larger 195 were designed with winglets. Both transonic wind-tunnel testing at DNW in The Netherlands and at TsAGI facilities in Russia showed significant drag reductions provided by some winglets configurations under investigation.

**Trailing vortices and downwash**

A vortex in general terms is the rotational motion of fluid, often comprising a strong region of low-pressure in its core. Wake vortices are generated whenever an aircraft produces lift. The principal structure of the wake downstream from a wing comprises a trailing vortex pair resulting of the merge of all vortices shed from the wing trailing edge with the tip vortex. Each vortex of the pair is formed in the vicinity of the wingtip because the tip vortex attracts the remaining weaker vortices. This structure may change if flaps are deflected (Figs. 1, 2, 3). In this case, two vortex pairs will be observed. In Fig. 1 it can be noted that only the outboard vortex cores were made visible by the water vapor condensation due to the pressure drop existent in this region. Fig. 3 reveals vortices originating at the wing flaps of a BAe-146 airliner.

The vortex wake produced by aircraft is more complicated than had been thought and may produce unforeseen turbulence in the air. Such flow structures play an important role in flight safety, since they can induce large rolling moments on other neighboring aircraft, and are known to cause loss of maneuverability control and fatalities. In rare instances a wake encounter could cause inflight structural damage of catastrophic proportions. However, the usual hazard is associated with induced rolling moments, which can exceed the roll-control authority of the encountering aircraft. In flight experiments, aircraft have been intentionally flown directly up trailing vortex cores of larger aircraft. It was shown that the capability of an aircraft to counteract the roll imposed by the wake vortex primarily depends on the wingspan and counter-control responsiveness of the encountering aircraft.

Continuing growth of air traffic has made "wake vortex" one of the most challenging technical issues in modern civil aviation. The requirement for reduced separation distances on densely flown approach routes is closely linked to the hazard caused by wake-generating aircraft and its safety impact on following aircraft. Great efforts have been made in recent years to increase the knowledge base of aircraft-generated wakes. In the light of a new class of high capacity airliners to enter service in the next decade, research must intensify even more to better understand wake physics, so that vortex-related hazards can be quantified and means for hazard reduction implemented. A major role to achieve this goal is seen in utilizing modern visualization techniques that became available in recent years.

The strength of the wake vortex is governed by the weight, speed, and shape of the wing of the generating aircraft. However, as the basic factor is weight, the vortex strength increases proportionately with increase in aircraft operating weight. Peak vortex tangential speeds up to almost 100 meters per second have been recorded. A lifetime of
several minutes and a length of 30 km behind large planes have been recorded and are widely known, though the vortex energy has reached a very low level. Even bigger aircraft can be damaged by wake turbulence. This was the case for a MD-11 airliner during a VFR approach at Runway 24R of an unspecified U.S. airport. The airplane was flying 5.6 km behind a Boeing 747 that was landing at Runway 25L. The parallel runways were 168 m apart and staggered; with the threshold of Runway 24L located 1,312 m beyond of threshold of Runway 24R. The MD-11 was 31 m above the ground when it rolled left, then right and developed a high sink rate. The captain initiated a go-around, but the airplane contacted the runway and bounced-back into the air. The captain discontinued the go-around and landed the airplane on the runway. The MD-11’s aft lower fuselage and aft pressure bulkhead were substantially damaged. The accident was ascribed to improper planning by the MD-11 pilot-in-command. The U.S. Aeronautical Information Manual recommends that when an airplane is following a larger airplane on parallel approaches to runways closer than 763 m, the trailing airplane should remain at or above the other’s airplane flight path, to avoid the other’s airplane wake turbulence.

Evidently, the energy necessary to generate the vortex structures and wing downwash is driven out from the powerplant. In other words, a large amount of drag is generated, called drag due-to-lift or induced drag. Induced drag represents 30-40 percent of the total drag of a transport airplane at cruise condition so it has a big impact on fuel consumption. The induced drag is directly proportional to square of the lift coefficient. Therefore, takeoff, climbing, long-range cruise, holding are phases of flight where the induced drag is high because the lift coefficient is also high.

Airbus undertook a special effort to keep the A380 wake vortex no stronger than the 747 so other aircraft wouldn't require extra intrail separation from it. Engineers reviewed NASA, European and Russian TsAGI studies. They noticed that the two-engine Airbus A330 and four-engine A340 have different vortex patterns even though they have the same wing, owing to changes in location of the flaps and engines. They also observed that the A320 and A321 have different patterns, apparently because one model has single-slotted and the other, double-slotted flaps. Airbus reports the location of the flaps, ailerons and engines on the A380 was adjusted to minimize the wake vortex, and it is estimated to be a few percent stronger than the 747-400's.

**Winglet benefits**

Winglets belong to the class of wingtip devices aimed to reduce induced drag. Selection of the wingtip device depends on the specific situation and the airplane model. In the case of winglets, the reduction of the induced drag is accomplished by acting like a small sail whose lift component generates a traction force, draining energy from the tip vortices.

The wingtip might be considered a dead zone regarding to the aerodynamic efficiency, because it generates lots of drag and no significant lift. The winglet contributes to accelerate the airflow at the tip in such a way that it generates lift and improves the wing loading distribution, which is related to the induced drag. In addition, the aircraft will fly at a slightly lower angle of attack for the same lift coefficient. Thus, it should always be possible to obtain significant drag reductions by using wingtip devices even for high-aspect wings. The Airbus A-340 development illustrates this assumption well. This airliner was originally designed with no winglets placed onto its high aspect-ratio wing. However, the A-340 was initially intended to use two ultra-high-bypass engines from International Aero Engines (IAE), the IAE Superfan, a highly fuel-efficient concept. This configuration was dropped and Airbus adopted four smaller less-efficient engines, instead. At this point, the European manufacturer installed winglets on the A-340 in order to keep the original envisaged range. Airbus is also releasing artist impressions of the A-380 high-capacity airliner that show endplates placed at the wingtips in a similar fashion as for the smaller A-320.

A key advantage of winglets is that they increase performance while only fractionally increasing the root bending moment on the spar compared to a wingspan extension. It has to be taken into account that a wingspan extension requires anti-ice or deice devices, which in turn demand additional bleed air from the engines increasing thus fuel consumption. A way to avoid this design issue is to employ raked wingtips like Boeing did for its 767-400 aircraft. Thanks to winglets the aircraft will climb to initial altitude faster and save fuel due to a more efficient climb profile. Otherwise, the aircraft can takeoff at lower thrust settings, which reduces the aircraft noise footprint and extends engine life. Aircraft takeoff weight is sometimes limited by the requirements in the second climb segment, which occurs after the
landing gear is retracted. In some situations, there is enough field length but the airline has to leave some passengers on ground because the aircraft cannot fulfill the climb requirements especially on hot days. In many cases winglets help to minimize this kind of problem or even solve it. In the case of some business jets, the winglets can enable the aircraft to reach maximum cruising altitude avoiding a fuel consuming “step-climb”.

Agricultural aircraft (Fig. 3) operate at high lift coefficients most of the time. At this condition winglets could significantly reduce fuel burn by allowing higher lift-to-drag ratios. In addition, the counter-rotating vortex pair, which becoming stronger at such flight conditions, contributes to lower the productivity of the spray runs. The drift of pesticides from the target site during aerial spray applications is a source of environmental concern due to its potential human health impacts, downwind contamination and damage to crops and livestock, and endangering ecological resources. Winglet and some wingtip devices prevent the tip vortices to erratically disperse the chemicals contributing this way to minimize the related adverse environmental effects.

The general aviation has seen increasing adoption of winglets among traditional planes on the market. Some of the new aircraft were also designed with winglets like the Pilatus PC-12. The main reason behind this new trend is related to the improvement of the rate-of-climb, since piston-powered aircraft have usually very low climb rates. Additional claimed benefits are increased takeoff ramp weight, and lower stall speeds. A direct effect of lowering the stall speed is a safer aircraft. A company that offers a winglet kit for the Beechcraft Duke published that its product enabled the lowering of the stall speed by 6 KIAS (flaps at 30°) and the increasing of the maximum gross weight by 102 kg.

A crucial factor to include in the overall equation is the cost of retrofitting the winglet in the first place. If the only operator consideration is the fuel cost savings over time, then there is no point in spending money on winglets, where the useful life remaining in the airframe time is less than would be required for the fuel savings to offset the original investment. On the other hand, if this is the deciding factor, then owners of older aircraft should make sure their aircraft have sufficient life remaining for the winglet’s fuel burn reductions to payback the installation cost. Furthermore, all this assumes that the winglet never gets damaged during this period. If, however, it does become damaged, for example by collision with an errant ground-support truck, then the originally economic justification could fade.

In the early days of the winglet era, only business jets adopted winglets, mostly due to aesthetic reasons. Fig. 4 shows the drag reduction for the Gulfstream III, one of the pioneer corporate aircraft to adopt winglets. The flight test conducted at Mach number of 0.75 indicates a greater drag reduction than the wind-tunnel test had indicated. Here, the deformation of the winglet due to the high loads on the wind-tunnel model can contribute to blanket part of the benefits of the winglet installation due to the departure of an optimal designed geometry. The Flight test conducted at a higher Mach number, in this case 0.775, shows the degradation of the winglet contribution to the overall performance caused by the presence of shock waves on the winglet planform.

![Fig. 3 – Ipanema EMB-202 agricultural aircraft (Photo Embracer).](image)

![Fig. 4 – Drag reduction provided by winglets for the Gulfstream III business jet.](image)

![Fig. 5 – Effect of winglets on takeoff field length of the Boeing 737-800. Source: Boeing Aero Magazine.](image)
Currently, a large number of recent commercial and military aircraft projects were already designed with winglets. There are some companies offering winglet retrofits for existing products. Boeing Co. contracted a third company to design, test and manufacture the winglets of its large-capacity business jet family, known as Boeing Business Jet (BBJ). However, for mainline 737 operators operating the aircraft on short sectors, where most of time is spent climbing and descending, and less time at the cruise condition, the extra weight of the installation, the added wetted-area and the parasitic drag, could possibly negate aerodynamic benefits in the cruise condition, remaining only the advantages for takeoff and climb flight phases. In any case, Boeing reports that a B737-800 equipped with blended winglets would be able to fly further burning 3 to 5% less block fuel. Besides these benefits, the 737-800 is also able to carry up to 6,000 lb more payload. According to Boeing Co., derived benefits include a reduction in noise near airports (-0.5 to -0.7 EPNdB at cutback, sea level), lower engine maintenance costs, and improved takeoff performance at high-altitude airports and in hot climate conditions. Fig. 5 shows the impact on field length due to the addition of winglets. The effect is more noticeable on takeoffs at airports located at higher altitudes.

Fig. 5 – Winglet drag reduction for the AEW&C variant of ERJ 145.

**Design highlights**

Despite the benefits of winglets, there are some drawbacks that need to be addressed. For example, the bending moment at the wing root is higher and may require additional structural wing reinforcements. This especially is the case when an airplane model has been designed and certified without winglets. The magnitude of the winglet-induced load increases and its distribution along the wing can significantly affect the cost of modifying the wing structure. The winglet also generates viscous and induced drag, which should be minimized and obviously avoiding offsetting the induced-drag reduction caused by the winglet itself on the configuration.

Winglets could also contribute to slightly worsening of the aircraft Dutch-roll. Too much dihedral and insufficient vertical stabilizer area cause Dutch roll. There is too much spiral stability and insufficient directional stability. The cure for spiral divergence, reducing vertical stabilizer area and/or increasing dihedral, thus makes the aircraft more prone to Dutch roll. The cure for Dutch roll, increasing vertical stabilizer size and/or reducing dihedral, makes the aircraft more directionally stable and more prone to spiral instability and spiral divergence. As is usual when designing aircraft, some compromise must be made, and the aircraft is then designed around what is seen as the best overall performance. Winglets produce a substantial amount of effective dihedral. If winglets are mounted on a plank planform wing, and the wing is then yawed, the forward winglet produces some amount of lift toward the wing. The trailing winglet will produce lift away from the wing. The side of the winglet that is facing away from the oncoming flow therefore has an area of reduced pressure. Adjacent areas of the wing are affected as well. The gross result is a rolling moment, which is directly related to the amount of yaw. This effect is kept when the wing is swept. From Nickel and Wohlfahrt, the skid-roll moment for a wing with winglets is the...
same as that of a conventional wing with the equivalent dihedral angle, EDA:

\[
EDA = \frac{20h_w}{s}
\]

where

- \( EDA \) = equivalent dihedral angle;
- \( h_w \) = the height of the winglet;
- \( s = \frac{b}{2} \) or wing’s semispan.

Wing sweep also contributes to increase the effective dihedral angle. Swept wings, particularly those that use winglets may suffer from excessive effective dihedral and Dutch roll effects.

Another important issue to be taken into account is the impact of the winglets on the flutter characteristics of the configuration. According to Boeing Co.,\(^4\) in order to meet flutter requirements with minimal structural changes for the Boeing 737-800 winglet installation, additional wingtip ballast was mounted on the front spar to counteract the incremental weight of the winglet located aft on the wing. The use of wingtip ballast depended on the structural configuration of the wing. In some cases, ballast was simpler and more cost effective than structural modification of the wingbox. No wingtip ballast is required for the BBJ configuration; 75 lb of ballast per wing is required for each production winglet on the 737-800 commercial airliner; 90 lb of ballast is required per wing for 737-800 retrofit. For the ERJ 145XR and Legacy business jet, which are derived of the successful ERJ 145 regional jet, the winglet installation required no addition of ballast to the wings.

The design of the winglet airfoil imposes a great challenge to the aerodynamicist because the winglet surface is usually highly loaded and works under a large range of Mach number and lift coefficient. Because of the latter consideration, a slightly nose droop of the airfoil is recommended to avoid unwanted suction peaks and drag creep. It is also highly desirable that the winglet starts to stall after the wing stalls. Apart from the airfoil, there are few key parameters that have to be taken into account to optimize the winglet design: cant angle, twist distribution, sweepback, taper ratio, root incidence angle, and aspect ratio. For a winglet configuration aimed to a transonic wing, it is mandatory the absence of moderate to strong shock waves or even Mach numbers above 1.2 on the winglet surface. To accomplish this, the aerodynamicist has to avoid high toe-in and twist angles of the winglet planform.

However, for doing so, the lift produced by the winglet and therefore the associated drag reduction will diminish at lower speeds. That is the point where CFD could help by enabling fast parametric configuration studies. The CFD solvers shall be able to correctly treat the complex flow patterns found at wingtips.

There are some other considerations not directly related to the drag reduction but which can impact it somehow. For example, in specific cases, the winglet may have to house anti-collision and navigation lights (Fig. 8). Winglets also require protection against lightning, considering they exert some attraction for them. Although winglets frequently cause an increase in maximum lift coefficient, the final configuration must keep the maximum lift coefficient of the wing without winglets, at least. The winglets appeared to prevent the wing tip from stalling first, thus reducing the tendency to roll-off, which was also exhibited in stalls with moderate amounts of sideslip of some subsonic aircraft.

Some designs with no smooth transition between the winglet and the wing employ some fairing with a triangular-shaped trailing-edge extension to minimize interference and wave drag (Fig. 9). The fairing acts increasing the local Reynolds number and reducing the airfoil section maximum thickness. At the junction the flow is highly accelerated and at transonic speeds strong shock waves could appear.

Fig 8 – The Embraer 170 airliner has the navigation lights casing placed at the wing lower side in order to minimize interference drag (Photo by Collin K. Work).
Fig. 9: Some conventional designs employ an extended triangular-shaped trailing edge at the wing/winglet junction (Photo Embraer).

The Boeing Co. employed a raked wingtip for the 767-400 airliner instead of whitcomb-like winglets and Fairchild Dornier had selected the so-called Super Shark winglet for the Envoy 7 business jet (Fig. 10), which would be a derivative of its 728JET airliner. Compared to the smaller B-737-800 the raked wingtip provided more percentual drag reduction4 (Fig. 11). However, this figure must be taken carefully, since both aircraft have different mission profiles and therefore lift coefficients at the cruise condition. In addition, raked wingtips may require wider hangars and the some benefits of higher aspect-ratio wings in place of wingtip devices will certainly be overcome by the demand for additional engine bleed air in order to deice the extended wingtip.

Besides the AEW&C aircraft, Embraer installed winglets on two other variants of the ERJ 145 regional jet: the 3,100 nm-capable Legacy business jet and the ERJ 145 XR, which has more powerful engines and an increased maximum takeoff weight for greater range. The twinjets of the new aircraft family 170/190 were designed with winglets from the beginning. Winglets are being also considered for a new ERJ 145 maritime-patrol variant of the ERJ 145 airliner.

Computational fluid dynamics

Embraer employed the XFOIL10 (Fig. 12) and MSES7,8 codes from Massachusetts Institute of Technology (MIT) to design the airfoil of the winglets. The commercial fully unstructured finite-volume FLUENT3 code from Fluent Incorporated, Lebanon, New Hampshire, was employed to analyze the three-dimensional flow around the winglet. Fig. 13 shows typical domain boundaries of the computational model constructed for the FLUENT code. Parametric studies were conducted to determine the best shape and incidences for the winglet geometry. The FLUENT code was very useful in the designing of the transition surface between the winglet and wing.

Fig. 10: Super Shark Winglet of the Envoy 7 business jet.

Fig. 11: Drag reduction of wingtip device. Source: Boeing Aero Magazine

Fig. 12: Viscous flow calculation around a winglet airfoil with XFOIL ($M_\infty = 0.65$, $C_l = 0.50$, Reyn = $8 \times 10^6$).

Fig. 13: Computational domain used for an external aerodynamic calculation.
Regarding the ERJ 145 and its commercial derivatives, a new, thinner, winglet airfoil had to be designed as well as the toe and twist angles of the winglet planform were modified due to the flight regime at higher speeds. A preliminary winglet and the transition surface were created with the CATIA CAD program. Then they were exported to the Gambit grid generator, which was used to produce an unstructured triangular surface mesh. After that, this grid was imported into the spatial mesh generator T-GRID and a mesh consisting of one million cells was generated. The analytical capabilities of T-GRID were helpful in identifying and correcting skewed faces that could decrease the accuracy of the model and increase its execution time. Once the mesh was complete, the CFD calculations were performed on a Silicon Graphics Origin 2000 server. Fig. 14 shows Mach number contours on a computational model of the ERJ 145 airliner.

The addition of the winglet contributes to accelerate the flow at the portion of wing close to the tip. Fig. 15 illustrates this situation well for one of the first design attempts of the Legacy’s winglet ($M_\infty=0.76$). Here, for the station located at 94% of the semispan a shock wave located in the aft region caused by the presence of the winglet can be observed from the pressure coefficient distribution ($C_p$). Both flow calculations were performed at the same angle of attack. The shock wave causes the thickening of the boundary layer increasing in turn the interference drag. In order to avoid shock waves and their associated drag penalties in the region close to the basis of the winglet, a careful design of transition surface must be performed. The aerodynamicist can change the airfoil shape of the transition surface as well as other parameters such as its sweepback and incidence in order to obtain a good flow behavior.

In order to illustrate the effect of the winglet in reducing the wingtip vortex simulations were performed with FLUENT for an aircraft configuration with two different wingtips all other parts remaining the same. The left wingtip has a winglet and the right one was truncated (no fairing). Usually, a truncated wingtip will present a considerably stronger vortex core even when compared to a faired one. The FLUENT’s 2nd order explicit algorithm and the Sparlat-Allmaras turbulence model were selected for the flow calculation. According to some specialists, this turbulence model is more suited to external flow calculations. Fig. 16 shows vorticity magnitude contours in a plane behind the wing. The vortex magnitude of the truncated wingtip is considerably stronger compared to the one generated by the winglet. The Fig. 16 also shows that the stronger vortex is located inwards in respect to the wingtip revealing a considerably lower aerodynamic aspect ratio with regard to the geometric one. The calculations for this asymmetrical configuration at $M_\infty$ of 0.76 showed that the velocity in the vortex core in the vicinities of the truncated wingtip topped Mach number of 1.70 and in the region around the winglet was slightly supersonic. The pathlines at the truncated wingtip can be seen in Fig. 17. The ribbons clearly reveal the rotational nature of the flow leaving the wingtip.
After all numerical analysis were finished, Embraer was able to proceed with the structural project, manufacture and fit the winglet on an ERJ 135 prototype within four months starting just from the aerodynamic specification. Several important performance advantages were documented after a flight test campaign was conducted. One was a considerable increased weight capacity at takeoff. The test pilots reported a clearly noticeable faster climbing. The overall drag at maximum cruise condition was reduced by 4.5%.

Based on the good results obtained for the EMB 145 AEW&C and Legacy business jet, Embraer decided to install winglets to its newest 170/190 family of airliners. The Embraer 170, which was designed to comfortably transport 70 passengers and should be able to takeoff and land at London City Airport, is currently under certification. Three other variants will follow in this order: the stretched version for 86 passengers, the Embraer 175 aircraft; the Embraer 195 for 108 passengers, which has a new larger wing, and its shrink version for 96 passengers, the Embraer 190. Transonic wind-tunnel tests for the Embraer 170 in The Netherlands (DNW) and Russia (TsAGI) (Fig. 18) revealed more-than-expected drag reductions in the entire flight envelope provided for some of the tested winglet configurations.

The design of winglets for the Embraer 195 could incorporate improvements and innovative ideas strongly based on CFD analysis. Starting from the Embraer 170 final design a parametric analysis was performed with VSAERO from AMI Corporation, Seattle WA, which permitted the estimation of the reduction in induced drag for several configurations at subsonic conditions. Variations in planform, shape, aspect ratio, taper ratio etc. could all be tested and innovative designs analyzed (Fig. 21). After that, Fluent could be used for fine-tuning and verification of the different winglets at transonic speeds. With this process and using more powerful CFD hardware, it was possible to analyze tens of configurations in one month, resulting in improved designs and new innovative configurations which could result in more attractive options contemplating structural and manufacturing constraints. A key aspect was the combination of skilled CAD work, low fidelity analysis for configuration parametric analysis and high fidelity transonic tailoring using Fluent’s capabilities. As a result, the Embraer 195 program could have different options for the winglet design in reduced time.

Fig. 19 – Pathlines at a truncated wingtip of a test case configuration.

Fig. 20 – Mach contours on a computational model of Embraer 170. $M_\infty = 0.72$, $\alpha = 1.5^\circ$.

Fig. 19 - Triangular surface mesh of an Embraer 170 computational model.

Fig. 20 - Mach contours on a computational model of Embraer 170. $M_\infty = 0.72$, $\alpha = 1.5^\circ$.

Fig. 21 – A low aspect-ratio winglets were also investigated to the Embraer 195.
**Concluding Remarks**

The present work showed that winglets are becoming an important and common instrument to achieve performance improvements in the present highly competitive aircraft market.

Various aspects affecting the design of winglets were described and highlighted, ranging from airfoil characteristics to the shape and importance of correctly designing the transition surface between the wing and the winglet.

Embraer has successfully designed and installed winglets for several of its products with impressive results. For this task, CFD tools proved to be mandatory for an efficient design of winglets for transonic aircraft configurations. Extensive wind-tunnel testing and CFD has enabling the design of efficient winglets.

The experience gathered by Embraer and the widespread use of winglets in new aircraft designs allow to conclude that the old question of the feasibility of winglet adoption by designers is no longer valid. Instead a new issue concerning the choice of the best wingtip device configuration is currently in place.

**References**


